United States
Department of
Agriculture

Forest Service

Intermountain
Research Station

Research
Paper INT-372

November 1986

Pinyon-Juniper Site Quality and Volume Growth Equations for Nevada

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RESEARCH SUMMARY

Site quality and volume growth equations were developed for Nevada's pinyon-juniper (P-J) woodlands. A site index equation was built from a relationship between tree height and diameter. Two types of stand volume growth equations were constructed. Periodic annual volume growth was predicted from total crown volume, juniper crown cover, basal area, and quadratic mean diameter data. The other type of growth, long-term average annual yield from fully stocked stands, was predicted from site index.

ACKNOWLEDGMENTS

Data for this study came from lands managed by the U.S. Department of the Interior, Bureau of Land Management (BLM). Special thanks to Dave Schmidt and Steve Langdon, former temporary employees of the Intermountain Research Station, who felled and measured the study trees.

Cover Photo: Pinyon-juniper on the Elko, NV, BLM District, by Skip Ritter

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INTRODUCTION

In recent years, land managers have become increasingly aware of the potential value of the 42 million acres of pinyon-juniper (P-J) woodlands in the Rocky Mountain States. Inventories of P-J recently were done for the first time in Nevada, Idaho, Utah, Colorado, New Mexico, and Arizona. However, these inventories were conducted without procedures to estimate site quality and wood volume growth because adequate methods were unavailable. As an attempt to fill this information void, this study was initiated using a more intensively measured subsample of plots from the Nevada P-J inventory. The study was an exploratory effort to develop site quality and stand growth equations for use in P-J inventories.

PREVIOUS WORK

Two ideas about site quality in P-J woodlands have been proposed. The first is structural tree support theory. McMahon (1973) put forward a structural support theory, finding tree height proportional to basal trunk diameter raised to the two-thirds power. Tausch (1980) generalized McMahon's finding in a simple plant dimension model and proposed using the proportionality constant as a site quality measure:

$$Y = a \cdot X^b \tag{1}$$

where

a = the proportionality constant or site quality measure

Y, X = dimensions of plant parts

b = a theoretical constant, unaffected by site quality and plant succession.

For singleleaf pinyon in Utah and Nevada, Tausch (1980, p. 127) found basal diameter and crown volume to be promising plant dimensions to use for X and Y in equation 1.

Daniel and others (1966) used a site quality measurement strategy somewhat related to the structural support theory. They developed pinyon site index curves based on the relationship between height and basal diameter dimensions on dominant trees.

The second idea of P-J site quality determination involved the growth of P-J woodlands. Meeuwig and Cooper (1981) defined a P-J site quality index as the total basal area growth of all trees per acre, per decade, in fully stocked stands. They defined as fully stocked those stands with undergrowth shrub and grass vegetation less than 10 percent of the total plant cover (trees, shrubs, and grasses). Because undergrowth is more than 10 percent of the total plant cover in many P-J stands, Meeuwig and Cooper developed a basal area growth prediction equation from topographic and soil measurements. However, this equation explained only 42 percent of the variation (R^2 = 0.42) in their data.

Another site index involving growth was Howell's (1940) use of average P-J basal area. Howell postulated that total basal area of a stand is an indicator of site quality when all trees average 5 inches at basal diameter. He modeled this by multiplying basal area by five times the reciprocal of average diameter when stands had an average basal diameter other than 5 inches.

Volume growth for individual P-J trees was examined by Meeuwig and Budy (1981). They developed growth equations from diameter, height, crown, and radial diameter growth measurements. Meeuwig and Cooper (1981) constructed a potential stand growth equation for fully stocked stands using basal area growth as the input variable.

Previous site quality and growth work has not been applied to P-J inventories because the results either were presented in a nonusable form or required impractical field measurements. For example, the site index graphs reported by Howell and Daniel and others were not accompanied by equations. Tausch's ideas have not yet been tested against data. And the equations constructed by Meeuwig and coauthors required 10-year diameter growth measurements for all or most trees sampled in an inventory. Because P-J diameter growth is best measured from cores or cross-sections under magnification in a laboratory, measuring diameter growth in large P-J inventories is considered too costly.

In this study, three relationships were modeled to aid site quality and stand growth estimation in P-J inventories:

1. Site index was modeled from the proportionality between tree diameter and height.
2. Periodic annual volume growth (PAI) was modeled from easily obtained P-J inventory variables.
3. Potential long-term average yield (PLAY) of fully stocked stands was modeled from site index.

PAI was defined in the usual way (Husch and others 1982, p. 276) as average annual volume growth of the last 10 years for all trees in a stand combined into a per-acre expression. PLAY was a descriptor devised for this study (only for fully stocked stands) to describe individual tree volume divided by tree age for all trees in a stand combined into a per-acre expression. PLAY was used in place

of yield capability (Brickell 1970) to describe potential yield of P-J woodlands. Yield capability as defined by the Forest Service (Forest Survey) is the mean annual volume growth increment (MAI) attainable in fully stocked natural stands at the age of maximum MAI. An alternative to yield capability was needed because Meeuwig and Cooper (1981) found no indication of basal area growth (which is strongly related to volume growth) approaching some maximum value for fully stocked stands up to 240 years old—the oldest stands they located in Nevada.

DATA COLLECTION

Singleleaf pinyon (*Pinus monophylla* Torr. & Frém.) and Utah juniper (*Juniperus osteosperma* [Torr.] Little) trees were sampled from 44 study plots in Nevada (fig. 1). Field measurements for this study were taken as a secondary task of a Forest Service quality control crew that was checking a U.S. Department of the Interior, Bureau of Land Management (BLM) woodland inventory. This arrangement required a flexible sample design to coordinate study plots with BLM inventory plots. Another constraint was the rigid time schedule (one plot per day) required by the Forest Service. To accommodate these constraints, two to four line-intersect transects (Meeuwig and Budy 1981) were superimposed on each 1/10-acre BLM plot included in this study. The transects, 77 feet in length, were laid out from a common origin 90 degrees apart. Trees selected on each transect were measured for diameter near ground line at 6-inch stump height (DSH), 10-year radial growth (two to four cores per tree measured under magnification), total height, crown volume form (coded for an ellipse, cone, sphere, or paraboloid), height to the base of the crown (HBC), maximum crown diameter (CRMX), crown diameter perpendicular to the maximum (CRMN), and numbers of basal stems. Only trees with at least one stem 3 inches DSH or larger were measured. For trees that forked at point of diameter measurement, an equivalent diameter was computed (Meeuwig and Budy 1981):

$$ED = \sqrt{D_1^2 + D_2^2 + D_3^2 + \ldots + D_n^2} \qquad (2)$$

where

ED = equivalent diameter

D = diameter of an individual stem

n = number of stems.

Trees selected along the last 40 feet of each transect (about half the trees sampled) were cut down to obtain age and volume. Total age was measured under magnification from a cross-section taken at 6-inch stump height. An outside bark volume was calculated from Newton's log formula (Husch and others 1982, p. 101) for all wood segments in a tree larger than 1.5 inches in diameter. Understory cover was obtained along the same transects used for tree measurements. Shrub and bunchgrass cover was measured by the line intercept method (Canfield 1941). Other grass and forb cover was measured by ocular estimation within two 1- by 5-foot quadrats spaced 20 feet apart along each transect. (More detailed instructions for the field measurements are documented in the 1980 Nevada Forest Survey field procedures, USDA-FS 1980.)

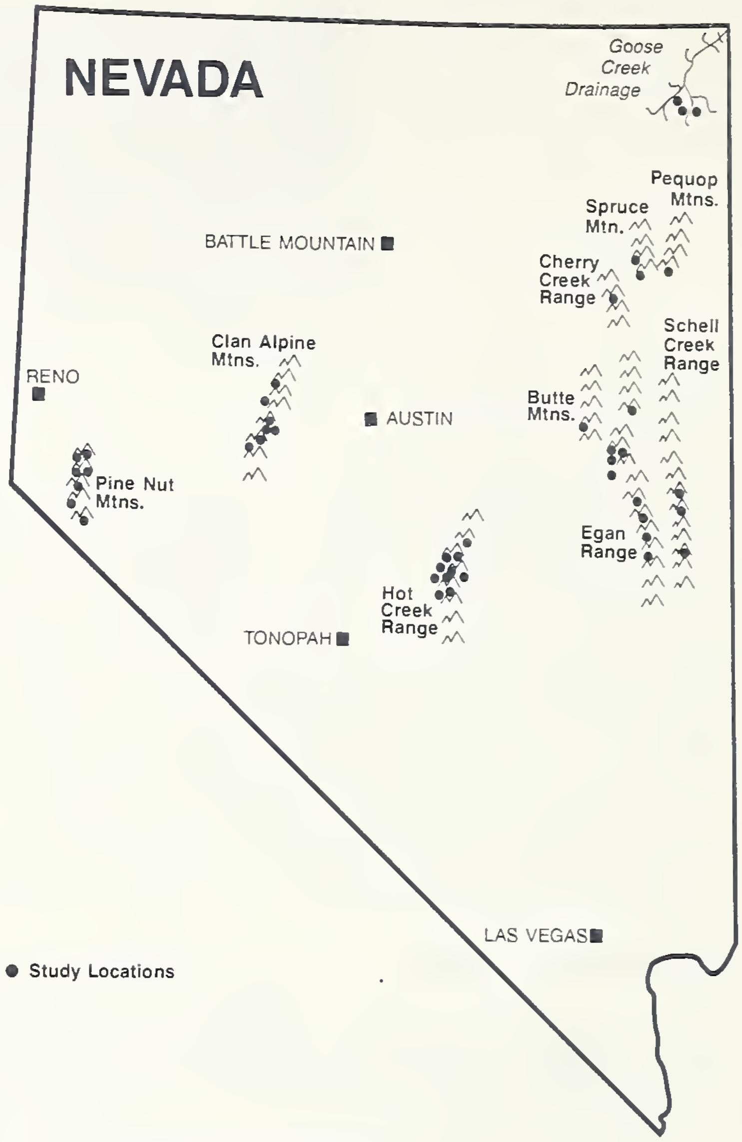

Figure 1—Map of study locations.

Besides field measurements, age and volume equations were needed to compute PAI and PLAY. By using the trees cut down for each study plot, prediction equations were developed for determining ages for those trees not aged, and for determining volume growth (eqs. 14 and 15 in the appendix). Two types of volume growth, PLAY and PAI, were computed for each tree. PLAY was computed by dividing a tree's estimated volume by its age. PAI was calculated from the difference between a tree's present volume and its past volume. Past volume for each tree was computed from the volume equation by back-dating DSH using 10-year radial growth measurements. This then was subtracted from the tree's present volume and the result divided by 10 to obtain PAI. All volume estimates for PLAY and PAI were determined from equations used for every tree (including those measured for volume) to maintain consistency between present and past volume estimation.

Site trees were identified for each study plot by computer selection. About four trees per plot having the largest height to DSH ratios were chosen.

The individual tree data were expanded to per-acre estimates for each study plot using Meeuwig and Budy's (1981) method. Canfield's (1941) method was used to expand the understory data. A summary of data and within-plot sampling variation for each study plot is given in table 1.

Table 1—Summary of the data for each of the 44 study plots

BLM District	Geographic area	Volume	PAI	Crown volume	Basal area	Quadratic mean DSH	Trees	Median stand age	Total tree cover	Shrub and grass cover	Trees sampled	Transects sampled	C.V. for basal area	C.V. for trees per acre
		Ft^3/acre	Ft^3/acre/yr	1,000 ft^3/acre	Ft^2/acre	Inches	No./acre	Years	Percent	Percent	No.	No.	Percent	Percent
Battle Mountain	Hot Creek Range	687	8	71	71	9.5	144	132	25	2	10	4	93	89
		761	13	100	107	8.7	260	95	38	8	8	2	78	76
		344	4	26	55	7.9	161	117	16	8	4	2	62	35
		718	6	64	69	13.2	73	173	22	6	6	3	96	93
		1,127	26	188	126	7.6	403	86	59	0	12	2	31	27
		265	4	34	37	13.1	40	207	12	13	4	4	167	172
		638	5	55	170	13.2	180	190	28	8	11	4	99	78
		498	7	110	71	8.8	169	82	37	8	12	4	65	69
		319	4	37	38	9.4	80	170	14	34	6	3	101	101
		541	5	77	133	8.3	357	160	36	0	16	3	17	35
Carson City	Clan Alpine Mountains	514	2	28	79	13.7	77	187	16	3	4	3	110	94
		286	9	90	40	5.4	250	46	33	14	7	2	109	89
		493	5	58	72	9.8	138	96	23	1	9	4	109	128
		1,308	11	150	113	9.1	250	163	42	15	12	3	96	85
		1,845	8	145	169	14.8	142	180	39	46	9	3	96	66
		1,701	15	182	141	10.6	228	132	43	12	8	2	82	74
		1,076	13	147	105	6.9	404	112	42	2	10	2	109	76
	Pine Nut Mountains	1,236	17	219	111	8.9	258	75	60	6	13	3	44	110
		1,119	11	198	84	13.7	81	99	47	8	10	4	121	101
		861	12	143	61	8.1	171	70	41	10	11	4	48	116
		1,162	18	214	81	11.6	110	121	51	2	12	4	73	71
		1,245	22	230	129	8.4	334	71	68	1	12	2	52	51
		279	4	74	50	9.5	102	89	30	11	9	4	121	62
		546	11	132	45	9.0	103	68	35	18	10	4	91	96
Elko	Cherry Creek Range	804	7	68	192	10.9	299	227	34	13	16	4	83	107
	Goose Creek Drainage	796	6	118	134	7.9	399	137	44	21	10	2	46	46
		1,309	8	170	273	11.7	363	210	61	7	11	2	30	65
		401	5	72	79	7.0	299	120	29	7	12	3	41	47
	Pequop Mountains	776	8	103	130	8.9	303	138	36	0	12	3	76	103
	Spruce Mountain	1,366	8	159	197	9.0	450	135	53	1	11	2	90	67
		320	4	53	77	7.2	272	164	25	16	13	4	150	68
Ely	Butte Mountains	336	3	53	76	9.0	169	149	21	3	6	2	116	115
	Egan Range	375	7	76	72	6.2	338	120	30	3	15	4	81	101
		573	13	98	92	6.1	461	80	35	0	15	3	65	87
		1,471	15	142	140	9.7	271	151	38	0	9	3	115	97
		1,383	16	173	141	8.7	340	101	44	4	9	2	110	88
		1,137	10	75	157	10.0	287	145	29	9	7	2	148	145
		803	6	79	112	10.8	175	174	28	1	8	3	95	41
		1,186	11	121	248	8.1	697	141	44	8	13	2	108	77
		668	6	39	122	10.4	205	193	15	10	9	4	122	130
		695	6	81	165	7.8	497	178	37	0	12	2	79	32
	Schell Creek Range	483	5	83	66	10.4	111	117	26	4	6	3	106	117
		304	2	39	75	9.0	168	164	16	15	6	3	78	142
		63	2	21	20	4.8	160	54	12	20	7	4	127	145

After the data were expanded, 16 of the 44 study plots were identified by Meeuwig and Cooper's (1981) criteria as fully stocked. These plots were considered to have maximum volume growth for their respective sites and were used for modeling PLAY.

All modeling analyses were done using regression analysis. Criteria for selecting the best prediction equations were maximum R^2, minimum C.V., and regression residual graphs indicating minimum variance and little prediction bias (see appendix for statistics definitions).

RESULTS

Site Index

Two site index model forms were considered:

$$\ln Y = a + b/X \text{ (Husch and others 1982)} \quad (3)$$

$$\ln Y = a + b \cdot \ln X \text{ (Tausch 1980)} \quad (4)$$

where

Y = height

X = DSH

a = regression coefficient interpreted as site index

b = regression coefficient.

Actual coefficient estimation of the site index equations was done for pinyon and juniper combined, and a separate a_i coefficient (site index) was estimated for each study site using dummy variables:

$$\ln Y = a_1 + a_2 + \ldots + a_i + \ldots + a_{44} + b \cdot Z + c \cdot SP \quad (5)$$

where

a_i = intercept for the ith plot, 0 otherwise

Z = $1/X$ for eq. 3, $\ln X$ for eq. 4

SP = 1 for pinyon, 0 for juniper

b, c = regression coefficients.

The best fitting equation relating height to DSH came from using equation 3 as a model form (eq. 6 in table 2). This equation was converted (for conversion see Husch and others 1982, p. 340) to a site index prediction equation (eq. 7 in table 2). Conversion required a reference (or base) DSH. Following Daniel and others (1966), a 10-inch DSH pinyon was selected as diameter reference.

The site index equation (eq. 6) was graphed (fig. 2) to compare differences between pinyon and juniper site indices. The graph showed that pinyon trees of the same diameter as juniper trees had to be taller to yield comparable site indices. Also apparent from the graph was less height distance (on the y-axis) between site index classes for the juniper curves than for the pinyon curves. This will probably result in less sensitivity of the site index equations for distinguishing between juniper site classes than between pinyon site classes.

The site index equation also was compared (in fig. 3) to a similar site index relationship constructed by Daniel and others (1966, p. 61). There was considerable difference for site indices above 18 feet.

Table 2—Site index and volume growth equations for Nevada[1]

Equation description	Equation formula	Regression statistics[2] R^2	$\sqrt{\text{MSE}}$	C.V.	n	Equation number
Height prediction	$\text{HT} = 1.0555 \cdot \text{SI} \cdot \exp - [3.6778 \cdot D_P + 2.5244 \cdot D_J - 0.3137 \cdot SP]$	0.83	1.99	13%	168	(6)
Site index	$\text{SI} = 0.9474 \cdot \text{HT} \cdot \exp[3.6778 \cdot D_P + 2.5244 \cdot D_J - 0.3137 \cdot SP]$	—algebraic manipulation of eq. 6—				(7)
Current growth	$\text{PAI} = \exp[-1.7821 + 0.7481 \cdot \ln(\text{CRNVOL}) + 0.2697 \cdot \ln(\text{BA}/D_Q) - 1.4238 \cdot \text{JCOV}]$	0.76	2.70	30%	44	(8)
Potential yield	$\text{PLAY} = -10.44 + 0.869 \cdot \text{SI}$	0.76	2.09	27%	16	(9)
Potential yield, upper bound	$\text{PLAY}_{ub} = -8.46 + 0.897 \cdot \text{SI}$	—tolerance point regression—				(10)

where

BA = basal area at DSH (ft^2/acre)

CRNVOL = crown volume per acre divided by 1,000 (1,000 ft^3/acre)

Crown area = $0.7854 \cdot \text{CRMX} \cdot \text{CRMN}$ (ft^2)

Crown volume = $0.5236 \cdot \text{CRMX} \cdot \text{CRMN} \cdot \text{CRHT}$ (ft^3)

CRHT = tree crown height (ft)

CRMN = tree crown diameter perpendicular to CRMX (ft)

CRMX = maximum tree crown diameter (ft)

DSH = tree diameter at 6-inch stump height (inches)

D_J = 1/DSH for juniper, 0 for pinyon

D_P = 1/DSH for pinyon, 0 for juniper

D_Q = quadratic mean DSH (inches)

exp = exponential function

HT = total tree height (ft)

JCOV = proportion of juniper crown area per acre

ln = natural log function

PAI = periodic annual volume growth averaged over 10-year period (ft^3/acre/yr)

PLAY = potential long-term average volume yield for fully stocked stands (ft^3/acre/yr)

PLAY_{ub} = 70th percentile maximum of PLAY (ft^3/acre/yr)

SI = site index (ft) referenced to 10-inch DSH pinyon

SP = 1 for pinyon, 0 for juniper

Volume = gross outside bark volume of all stems and branches larger than 1.5 inches in diameter (ft^3)

[1]These equations and definitions only apply to trees 3 inches DSH and larger.
[2]See appendix.

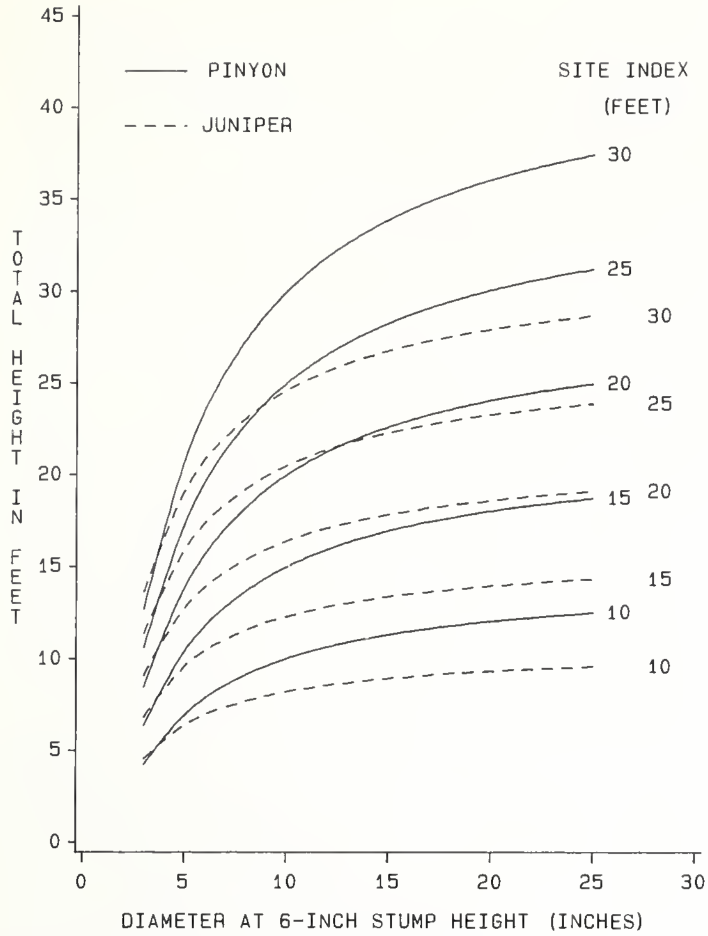

Figure 2—Height-to-diameter site index curves (reference tree is a 10-inch DSH pinyon).

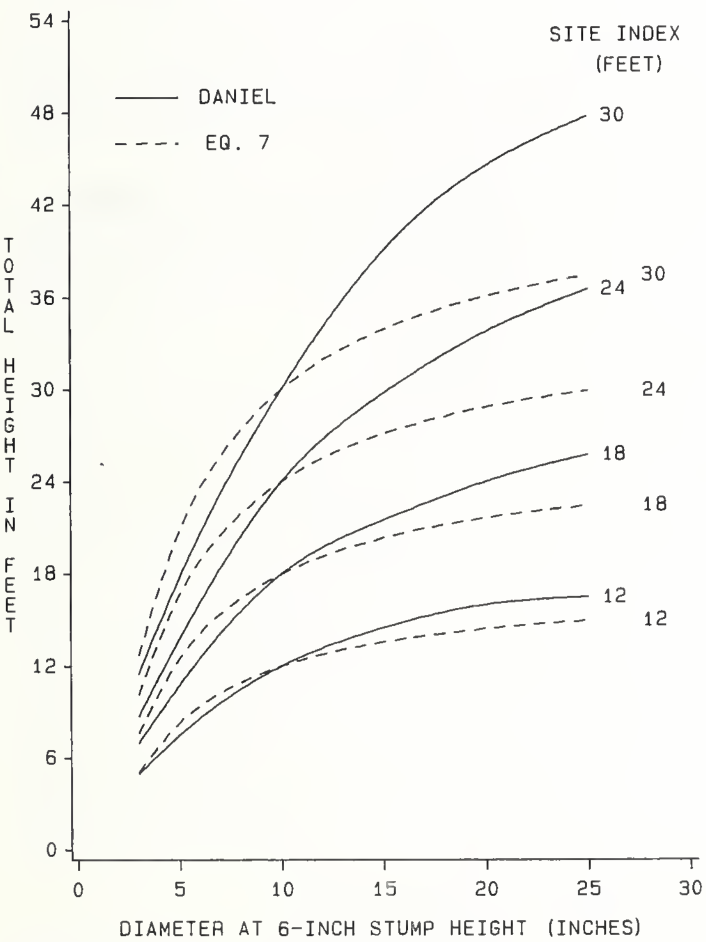

Figure 3—Comparison of Daniel and others' (1966) pinyon site index curves with corresponding pinyon site curves (eq. 7) from this study.

Volume Growth

Site index and other variables collected for this study were examined for PAI growth prediction. The best PAI prediction variable was total crown volume per acre, which explained more than 70 percent of the variation. Next best was a variable for the amount of juniper crown cover for each site. This variable accounted for a decreased growth rate proportional to the amount of juniper cover.

The regression analysis showed some gain from including a third variable in growth prediction models, but the data set was too small to clearly determine the best choice for this variable. Basal area growth had the highest R^2 among choices for a third variable in the PAI model. But because basal area growth is costly and somewhat impractical to obtain, a more practical third variable, basal area divided by quadratic mean DSH, was found. The final PAI equation (eq. 8) is listed in table 2.

PLAY, the measure of potential yield, was predicted from site index (eq. 9 in table 2). This equation gave a least squares average of annual volume yield for fully stocked natural stands.

Another PLAY equation was also developed using the tolerance interval concept from linear model theory (Graybill 1976, p. 270). This concept allows development of an equation that predicts values other than a conventional least squares average (like eq. 9). Statistical tolerance points (somewhat analogous to confidence intervals) enable determination of an upper or lower proportion (called upper or lower tolerance point) for the data distribution under study. In this study, upper 30 percent tolerance points at the 95 percent probability level were computed for each height-to-DSH site index value for fully stocked stands. This means a 30 percent tolerance point for a site index value is its expected maximum PLAY 70 percent of the time. Another regression equation (eq. 10 in table 2) was developed from the 30 percent tolerance points. When compared to the data (in fig. 4) this equation appeared a reasonable upper bound for PLAY prediction. This equation would be appropriate for assessment of the maximum or upper bound PLAY expected for a given site index.

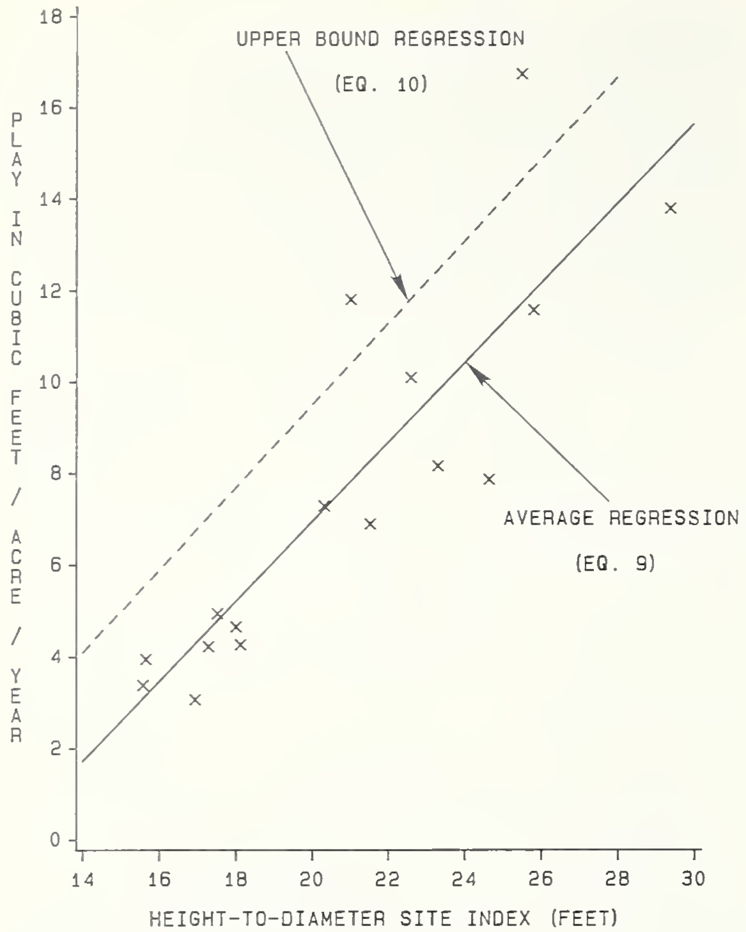

Figure 4—Potential long-term average yield (PLAY) prediction equations overlaid on data from fully stocked stands.

DISCUSSION

The site index and growth equations given in table 2 represent statistical descriptions of data in this study. Users of these results should consider two points not accounted for in the data analysis. First, because the equations in table 2 were mostly developed by empirical regression analysis, they may not apply outside the bounds of the data. Careful study of table 1 and figure 1 should be done before applying the site index and growth equations. A second, more subtle point concerns the line-intersect sampling method used to collect the data. During the analysis, I found suspiciously large blow-up factors from using transects to sample sparse P-J stands comprised of small-crown-diameter trees (see formulas in Meeuwig and Budy 1981). Because few transects per plot were used (see table 1) these problems were compounded. A comparison using thirty-nine 1/10-acre BLM inventory plots from the same sites as the study plots consistently showed larger values computed from the transect data for basal area and for trees per acre. This does not necessarily mean the line-intersect sampling method gives positively biased results for P-J. However, I suspect the relationships described by the equations in table 2 were somewhat affected by the line-intersect method. Had I used fixed-area plots, different model relationships or different equation coefficients may have resulted. Perhaps a more rigorous statistical treatment should be applied to P-J line-intersect sampling than that given by its first proponents, Meeuwig and others (1978).

Aside from sampling considerations, these study results at least meet the need for rough assessment of P-J site index and volume growth. Also the strong relationship found between crown volume and PAI should serve to stimulate future P-J growth research.

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APPENDIX

This appendix contains equations for goodness-of-fit regression statistics and for site-specific age and volume prediction.

Goodness-of-Fit Statistics

Because many models were developed with transformed data, goodness-of-fit statistics were recomputed after parameter estimation according to the following formulas:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n} (Y_i - \bar{Y})^2} \tag{11}$$

$$\text{MSE} = \sum_{i=1}^{n} \frac{(Y_i - \hat{Y}_i)^2}{n-p} \tag{12}$$

$$\text{C.V.} = \sqrt{\text{MSE}}/\bar{Y} \tag{13}$$

where

R^2 = coefficient of determination

MSE = mean square error from regression

C.V. = coefficient of variation

$\hat{Y}_i$ = predicted value of the observation retransformed to original measurement scale

Y_i = ith observation

$\bar{Y}$ = mean of all observations

n = sample size

p = number of model coefficients.

Age and Volume Equations

The following individual tree equations were developed for each plot for age and volume data summary:

$$A_i = \exp[3.6548 + b_i \cdot \ln(\text{DSH}) - 0.1638 \cdot SP] \tag{14}$$

$$V_i = \exp[-6.1090 + b_i \cdot \ln(\text{DSH}) + 0.6750 \cdot SP + 0.1719 \cdot \text{STEM}_\text{P} + 0.4519 \cdot \text{STEM}_\text{J}] \tag{15}$$

where

A_i = age (yrs) for trees in the ith plot

V_i = volume (ft^3) for trees in the ith plot, includes wood and bark for all stems and branches with diameters greater than 1.5 inches

SP = 1 for pinyon, 0 for juniper

DSH = basal diameter (inches) at 6-inch stump height

STEM_P = 1 for single-stem pinyon, 0 for otherwise

STEM_J = 1 for single-stem juniper, 0 for otherwise

b_i = coefficients estimated from data for the ith plot

i = 1 to 44 study plots

ln = natural log function

exp = exponential function

regression statistics

Eq. No.	n	C.V.	R^2
(14)	237	26%	0.75
(15)	247	33%	0.94

Chojnacky, David C. Pinyon-juniper site quality and volume growth equations for Nevada. Research Paper INT-372. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 7 p.

Site quality and volume growth equations were developed for Nevada's pinyon-juniper (P-J) woodlands. Trees at 44 sites were measured for basal stem diameter, crown dimensions, height, age, volume, and stem diameter growth. A site index equation was built from a relationship between tree height and diameter. Two types of stand volume growth equations were constructed. Periodic annual volume growth was predicted from total crown volume, juniper crown cover, basal area, and quadratic mean diameter data. The other type of growth, long-term average annual yield from fully stocked stands, was fit to site index in an equation. Equations are summarized in a table.

KEYWORDS: *Pinus monophylla, Juniperus osteosperma*, site index, periodic annual increment

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

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